COBE Observations of Interstellar Line Emission

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Abstract. The FIRAS instrument on the *COBE* satellite has conducted an unbiased survey of the far-infrared emission from our Galaxy. The first results of this survey were reported by Wright *et al.* (1991), and later conclusions were reported in Bennett *et al.* (1994). I report the results of analyses of this spectral survey, which includes emission lines from 158 μm C^+, 122 μm and 205 μm N^+, 370 μm and 609 μm C^0, and CO J=2-1 through 5-4. The morphological distribution along the galactic plane ($b = 0°$) for all the spectral line emission, and the high galactic latitude intensities of the strong C^+ and 205 μm N^+ emission are discussed. The high galactic latitude intensity of the 158 μm fine structure transition from C^+ is (C^+ 158 μm) $\approx (1.43 \pm 0.12) \times 10^{-6}$ csc $|b|$ erg cm^{-2} s^{-1} sr^{-1} for $|b| > 15°$, and it decreases more rapidly than the far infrared intensity with increasing galactic latitude.

1. Introduction

The interstellar medium is heated primarily by photons interacting with grains, producing hot electrons by the photoelectric effect (Watson 1972). Other heating is supplied by the excess energy given to electrons detached from atoms during photoionization, and by the excess energy given to atoms during the photodissociation of molecules. The hot electrons and atoms collide with the thermal particles and add energy. To maintain a steady state, this added energy must be radiated by the gas. The temperature of the gas will increase until the radiation process with lowest excitation threshold becomes effective. In the neutral atomic interstellar medium, the fine structure line of the C^+ ground state with an excitation energy corresponding to 91 K is the first effective cooling channel to open, so the C^+ line at 157.7 μm is expected to be strong (Dalgarno & McCray 1972). The ionization threshold for C is 11.26 eV, so it will be ionized even when H is neutral. O and N have higher ionization thresholds and will be neutral in H I regions. The ground electronic state of O is an inverted fine structure triplet, so the first transition from the ground state corresponds to the 63 μm line, and thus requires a considerably higher temperature for excitation.

In the warm ionized medium, the CNO elements will all be singly ionized. The cooling channel with the lowest excitation energy will be the N^+ line at 205 μm, but the 158 μm line of C^+ will still be strong. With a typical temperature of a few thousand degrees in the warm ionized medium, there will be many more channels for cooling, so none of these lines will dominate the cooling in the way the C^+ line dominates in H I regions.
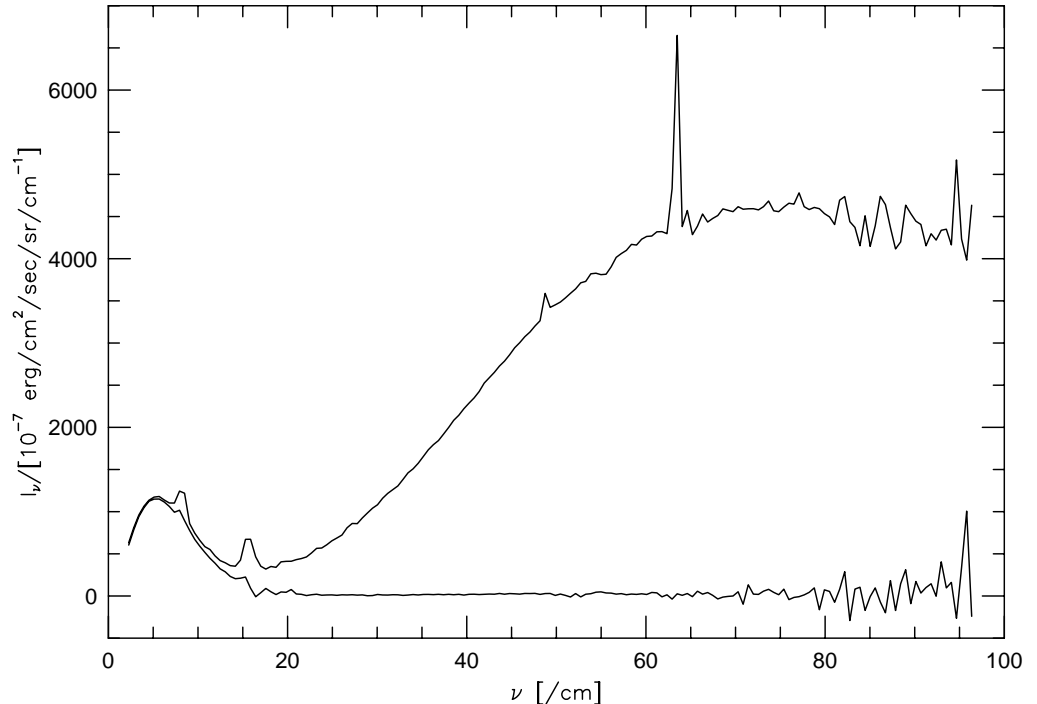
Figure 1.   FIRAS Right High Spectra of the Galactic Center and the
Lockman Hole.

In molecular gas, the rotational transitions of the CO molecule provide low
threshold energy cooling channels. The density and radiation field in regions
with CO favor the presence of neutral C instead of C^+. The ground electronic
state C^0 is a fine structure triplet with lines at 609 and 370 μm.

In this paper I will discuss the observations of these lines by the FIRAS
instrument on the *COBE* satellite. These data were first discussed by Wright
et al. (1991) which included the first detection ever of the 205 μm N^+ line.
Bennett *et al.* (1994) discuss the distribution of these lines around the sky.

2.   Observations

The FIRAS instrument is a polarizing Michelson interferometer first described
by Martin & Puplett (1970). Using free-standing wire grids as polarizers allows
a single instrument to measure many octaves of spectrum at once. Figure 1
shows spectra of the Galactic Center pixel and the pixel with the lowest N_H
(Lockman, Jahoda and McCammon 1986) taken from the Right High channel
of FIRAS. The high frequency part of the spectrum (> 20 cm^{-1}) was separated
from the cosmic signal by a dichroic beamsplitter, but the residual reflectance
of this filter allows one to see most of cosmic blackbody spectrum as well.

The FIRAS instrument uses bolometric detectors, and is thus approximately
equally sensitive to lines at any frequency. However, variations of filter trans-
mission and modulation efficiency modify this equality and must be determined
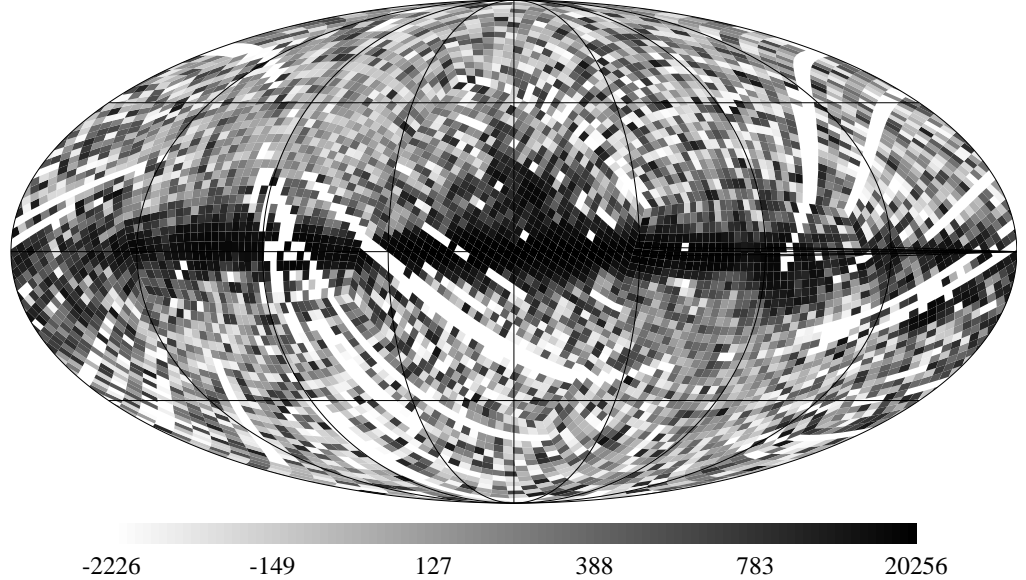
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C+ 158 Micron Line

| -2226 | -149 | 127 | 388 | 783 | 20256 |

Figure 2.   FIRAS C^+ line map in units of 10^{-8} erg/cm^2/sec/sr/cm^{-1}.

using calibration observations. The in-flight calibrators are essentially black-bodies, while the galactic spectrum is a very dilute modified Planck function. Thus the 50 part per million precision achieved in the search for deviations of the CMB from a blackbody (Fixsen *et al.* 1996) does not imply 50 part per million precision in the galactic dust and line fluxes. In particular, small ripples in the gain calibration could be confused with weak line fluxes in regions where the continuum is high.

The bright C^+ and N^+ lines are easily visible in the spectrum of the galactic center, and by fitting a line profile plus baseline to the spectrum of each pixel, maps can be generated. Figure 2 shows a map of the C^+ line flux.

Higher SNR on the galactic signal can be obtained by averaging all of the pixels together. But an arbitrary isotropic signal must be included in the fit, as well as the dipole variation of the CMB temperature. The following approach was used:

1. Make maps of the cosmic temperature variation and the galactic dust distribution using an initial guess for the mean galactic spectrum, $G_\circ(\nu)$:

$$I_\nu(l,b) \approx B_\nu(T_\circ + \Delta T(l,b)) + g(l,b)G_\circ(\nu)$$

2. Do a spectral fit to derive the isotropic cosmic spectrum, $I_\circ(\nu)$; the spectrum of the dipole, $D(\nu)$; and the mean spectrum of the galaxy, $G(\nu)$:

$$I_\nu(l,b) \approx I_\circ(\nu) + D(\nu)\cos\theta + G(\nu)g(l,b)$$

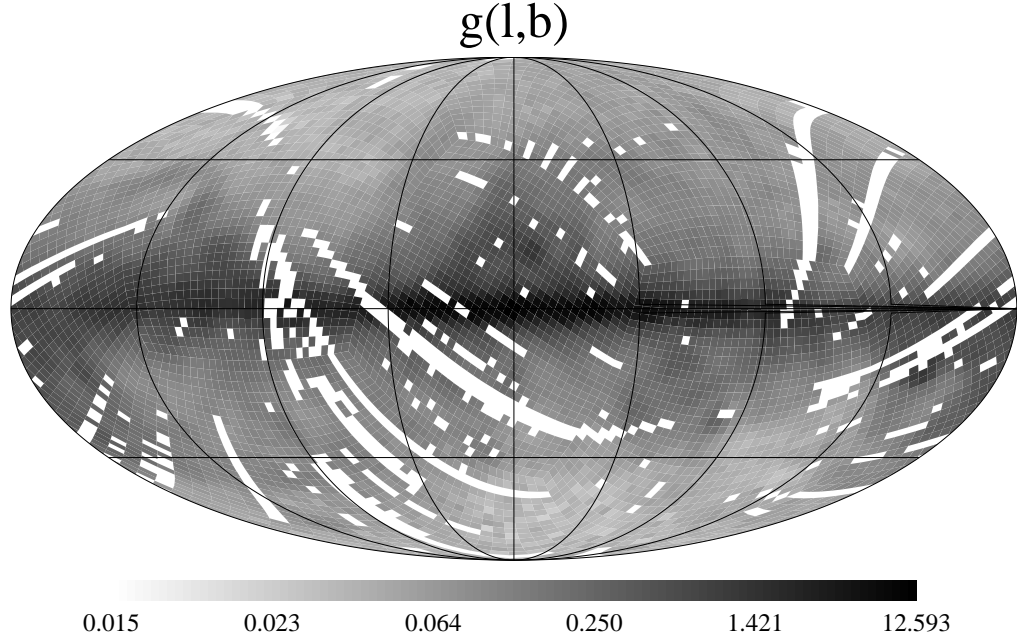where θ is the angle between the LOS (l,b) and the hot pole of the dipole.

Figure 3.   FIRAS dust map $g(l, b)$.

   3. Iterate using $G(\nu)$ instead of $G_{\circ}(\nu)$.

This procedure can be applied to a subset of the sky as well. Note that changes in the isotropic spectrum have no effect of the derived $G(\nu)$, which is determined solely from the variations of the spectrum with position on the sky.

   Wright *et al.* (1991) applied this procedure to the early data from FIRAS, and obtained a map of $g(l, b)$ over part of the sky and a spectrum $G(\nu)$ which was analyzed for line strengths and dust emission parameters. Figure 3 shows $g(l, b)$ for the entire FIRAS data set. Note that the polar flux (slope with respect to csc $|b|$) is 0.05 units on this map.

   The spectrum $G(\nu)$ derived only from data taken away from the galactic plane is given by Fixsen *et al.* (1996). Figure 4 shows this $G(\nu)$ after a modified Planck function is subtracted. The 3-2 and 4-3 CO lines have about the same strength in this spectrum as they do in the all-sky $G(\nu)$, while the 5-4 line is stronger. However, the SNR of this spectrum is quite low since all of the strong galactic signal has been ignored.

3.   CO Analysis

FIRAS detected the CO lines from 2-1 to 5-4. In terms of power in erg/sec, the 5-4 line is quite strong. The excitation of CO to the $J = 5$ level which has a radiative lifetime of only one day would seem to be quite difficult in the high galactic latitude molecular clouds seen by Magnani, Blitz and Mundy (1985). This excitation looks more reasonable if the CO line strengths are plotted in units of K-km/sec, as shown as in Figure 5. The almost perfect fit of these
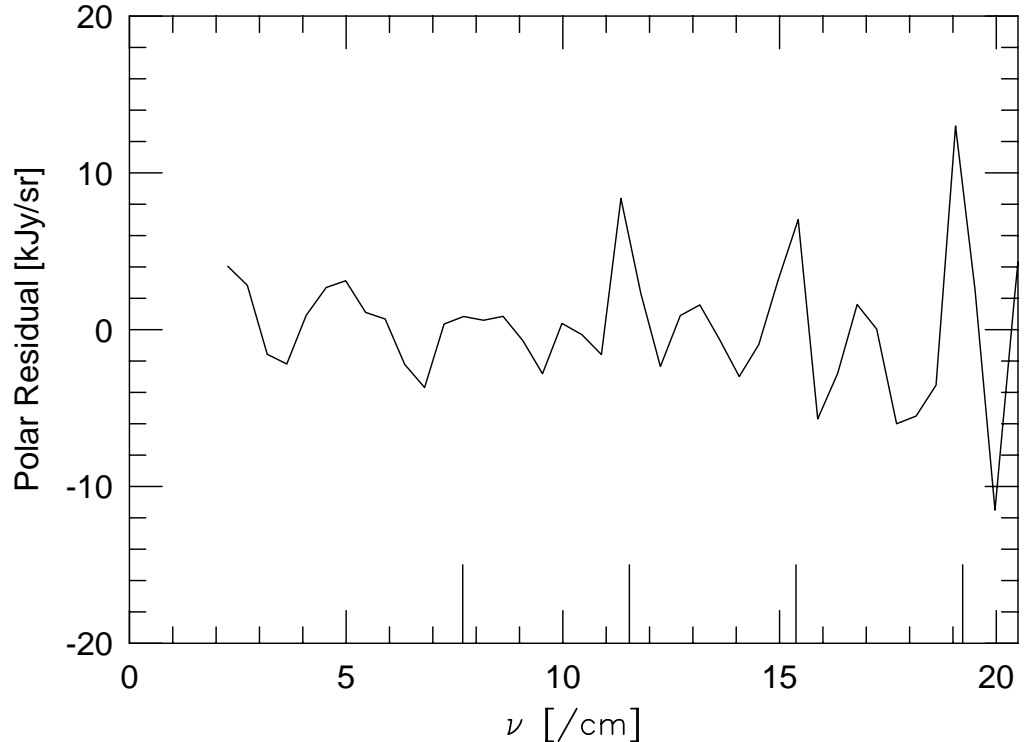
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Figure 4.   Fixsen *et al.* (1996) $G(\nu)$ minus a modified blackbody. The positions of the 2-1 through 5-4 CO lines are marked.

line strengths to $\exp(-bJ_U)$ (dashed line) suggests a thermal distribution, but since the energy of the CO levels is $\propto J(J+1)$ a mixture of temperatures is needed: the solid curve shows a model of optically thin CO with 88% at 5 K and 12% at 19 K. While this gives a good fit, the number of parameters equals the number of detected lines, so there are no remaining degrees of freedom. This two temperature model predicts a CO 1-0 line flux of 0.15 K-km/sec at the galactic pole. The standard ratio of CO 1-0 line flux to molecular hydrogen column density, $N(H_2)/I(CO) = 3 \times 10^{20}/(\text{cm}^2 \text{ K km/sec})$ (Young & Scoville 1991), gives $N(H_2) = 5 \times 10^{19}$ so this molecular gas is about 1/3 of the atomic gas at high latitudes. Blitz, Bazell & Desert (1990) estimate that the mass of the high latitude molecular clouds is 33% of the neutral atomic mass, implying that the FIRAS CO flux is due to the smeared out emission from the MBM clouds. The high latitude CO clouds have lower densities and lower extinctions than most molecular clouds, so a fluorescent cascade following vibrational or electronic excitation could provide most of the high-J CO.

4.   Conclusion

The FIRAS data on the Milky Way show the primary cooling mechanisms in the ISM. 99.7% of the power is radiated by dust heated directly by the interstellar radiation field. Gas in the ISM radiates 0.3% of the power in the C^+ line at
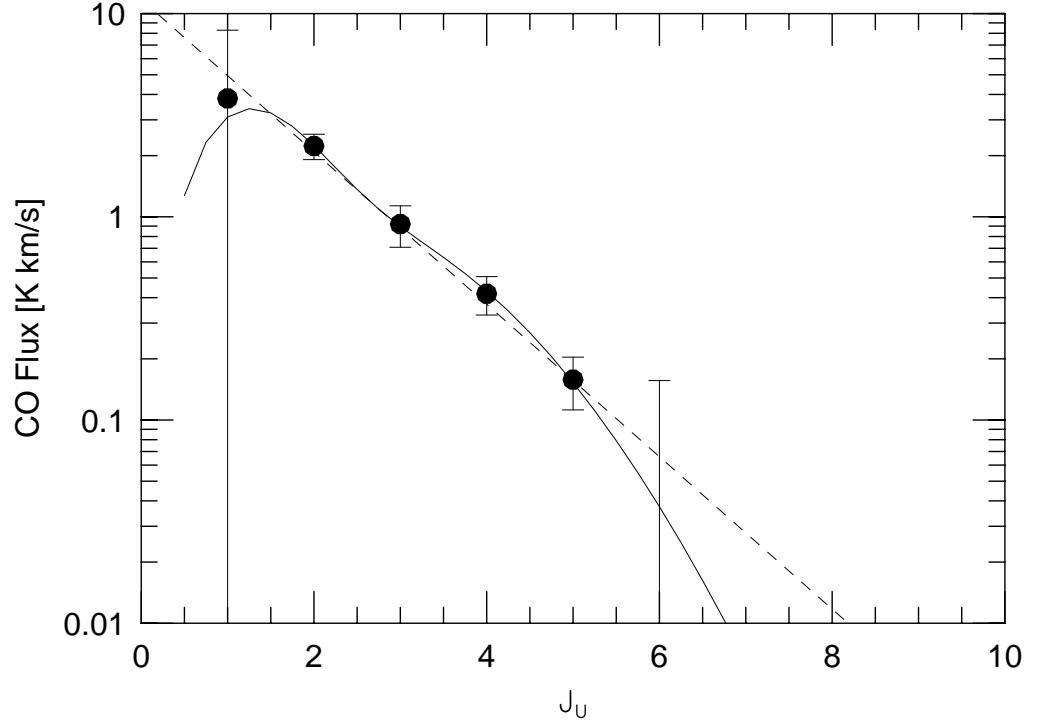
Figure 5.   FIRAS CO line strengths at $g(l, b) = 1$. The solid line shows a two-temperature model fit.

158 μm. The next most luminous species seen by FIRAS is N^+, with 0.03% of the power in the 205 μm line. C^0 and CO each radiate about 0.003% of the total power.

Discussion

Dr. Nakagawa: What is the temperature range derived from the CO lines?

Prof. Wright: The fit gives 5 K and 19 K.

Prof. Greenberg: When you say 88% of the CO at 5 K and 12% at 19 K do you imply that the CO is thermally coupled to the dust? I find this difficult to believe. Is this just a coincidence?

Prof. Wright: I hope so! Collisional heat transfer between gas and dust is quite slow.

Dr. Taniguchi: Your continuum and [C II] maps show an emission component North of the Galactic Center. What is it?

Prof. Wright: That is the Sco-Oph dark cloud complex.

Dr. Taniguchi: Is the northern extension at $l = 0$ and the southern extension at the anti-center due to warping of the disk?

Prof. Wright: No, those are both very nearby cloud complexes. The warp of the disk is a much smaller angle.

Dr. Giard: What is the upper limit on the ortho:para ratio in H_2O based on the apparent absorption at the Galactic Center?

Prof. Wright: First, we do not claim the absorption at $l = 0$ is real. But if it is, the line strengths shown in Figure 2 of Bennett *et al.* (1994) imply an equivalent width of $W_p = (3 \pm 4) \times 10^{-3}$ cm^{-1} for the para line at 269.3 μm while the ortho line at 538.3 μm has $W_o = (0 \pm 6) \times 10^{-3}$ cm^{-1}. A given equivalent width in the ortho line implies 4 times more column density than the same equivalent width in the para line because the frequency is half as large and the transition matrix element $|\mu_{ij}|^2$ is half as large. Thus ortho:para column density ratios ranging from 0 to more than 3:1 are all consistent with these equivalent widths. If both lines are optically thick, as seems likely, then W_o should be one half of W_p because of the frequency factor, which is also consistent with the observations. In the optically thick case we have no information on the ortho:para ratio.

Dr. Dwek: How do you interpret the two-temperature dust fit in terms of a physical dust model?

Prof. Wright: It could be caused by a shoulder in the dust emissivity law. This would explain the constancy of the cold dust temperature and the cold/warm opacity ratio.

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